An Overview of Indoor OFDM/DMT Optical Wireless Communication Systems

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***Abstract*—This paper is an overview of indoor OFDM (orthogonal frequency division multiplexing)/DMT (discrete multitone) optical wireless (OW) communication systems. Indoor OW OFDM/DMT systems can be classified into two groups. One group produces half-wave symmetry time signal at the output of the OFDM modulator by special assignment of subcarriers. Thus, allowing signal clipping at the zero level and avoiding the need of DC bias at the expense of data rate reduction. ACO-OFDM (asymmetrically clipped OFDM system) and PAM (pulse amplitude modulation)-DMT are two techniques from the first group. The second group assigns data to all possible subcarriers to increase the data rate. However, half-wave symmetry signals cannot be achieved and DC bias is needed to convert the bipolar signal to a unipolar signal before modulating the LED (light emitting diode) intensity. DC-biased OFDM and a novel technique, proposed in this paper, called *orthogonal PAM-DMT (OPAM-DMT)* that is an extension of the proposed PAM-DMT by using discrete sine transform and discrete cosine transform to transmit two orthogonal signals at the same time, are two techniques from the second group. This paper considerers a practical LED model and studies the performance of all these systems in terms of average electrical OFDM signal power versus bit-error-ratio (BER) in the presence of additive white Gaussian noise channel (AWGN). It is shown that LED clipping has significant impact on the performance of all these systems and the performance of these systems substantially depends on the considered modulation order.**

***Index Terms*—Optical wireless communication, intensity modulation, direct detection, OFDM, DMT, PAM, ACO, DC-biased, LED nonlinearity.**

I. INTRODUCTION

Next generation wireless communication systems (5G) will be based on several complementary access technologies and OW is expected to be essential in the 5G vision [1]. For example, bandwidth-intensive applications such as Internet multimedia streaming perform more effectively over networks with high bandwidth and data throughput. The radio frequency (RF) technology suffers from restricted spectrum availability and interference. Instead, OW technology can be considered motivated by the several benefits as compared to RF systems. These benefits include unregulated huge (THz) bandwidth, license-free operation, low-cost front-ends, and no interference with RF which makes it a preferred solution for RF-sensitive operating environments as in airplanes and hospitals. Besides, it is free of any health concerns as long as eye and skin safety regulations are fulfilled.

OW technology can offer infrared (IR) and visible light indoor links using commercially available LEDs and photo diodes (PDs). For OW links utilizing LEDs, the most viable modulation is intensity modulation (IM) and the most practical down-conversion technique is direct detection (DD) [2].

The performance of OW system depends on the propagation and type of system used. The basic system types fall into diffuse or line of sight (LOS) systems. In LOS systems, high data rates in the order of Gbit/s can be achieved [3], but the system is vulnerable to blockage/shadowing because of its directionality. In a diffuse OW system, several paths from source to receiver exist, which makes the system robust to blockage/shadwoing. However, the path losses are high and multipaths create inter-symbol interference (ISI) which limits the achievable data rate [2, 4]. A promising solution to combat multipath distortion and boost the data rate without any bandwidth or power expansion is by using OFDM technique.

OFDM for OW systems is proposed in [5–7] to support high data rates through parallel transmission of high order multi-level quadrature amplitude modulation (M-QAM) symbols on orthogonal subcarriers. OFDM systems are able to support high data rates without the need of complex channel equalizers and the time-varying channel can be easily estimated using frequency-domain channel estimation. In general, the output of the OFDM modulator is complex and bipolar. In IM optical systems, quadrature modulation is not possible. This means that the baseband signal must be real. Also, the OFDM signal envelope variations are utilized to intensity modulate the LED and the bipolar signal must be converted to a unipolar signal. Therefore, the OFDM commonly used in RF communications must be modified.

This paper provides an overview of existing OFDM modulation techniques suitable for OW communication. The performance of these systems are simulated via Monte Carlo simulations in the presence of AWGN channel and a realistic LED model. LED clipping effects at the maximum allowable AC voltage corresponding to the maximum allowable forward current and at the LED turn-on voltage obtained from the LED data sheet are considered.

In addition, a novel approach called OPAM-DMT, which is an extension to PAM-DMT [8] technique by using orthogonal discrete sine and cosine transforms is proposed. The scheme is shown to achieve twice the data rate as compared to PAM-

DMT.

The remainder of this paper is organized as follows: Section II discusses the existing OW OFDM techniques. Simulation results are presented in Section III. Finally, Section IV concludes the paper.

II. Optical Wireless OFDM Techniques

A general system model of indoor OW OFDM systems is depicted in Fig. 1.

The existing OW OFDM systems can be classified into two groups based on the subcarriers assignment and the bipolar-unipolar conversion techniques considered. In the first group, the subcarriers are assigned to produce a half-wave symmetry time signal. Therefore, bipolar-unipolar conversion is attained by clipping the resultant time signal at the zero level [8, 9]. These techniques are named *half-wave symmetry OFDM*. The second group assigns data to all available subcarriers. Thus, increasing the data rate as compared to the first group but the output signal is no longer symmetrical [5–7]. Hence, bipolar-unipolar conversion can be achieved by adding a certain DC bias. These techniques are named *DC-biased OFDM*. Details of half-wave symmetry OFDM and DC-biased OFDM techniques will be discussed in what follows.

A. Half-wave symmetry OFDM techniques

Two techniques are reported in literature where a half-wave symmetry OFDM time signal can be achieved. Namely, ACO-OFDM proposed in [9] and PAM-DMT proposed in [8]. In all considered systems in this paper, $q(k)$ raw data bits are to be transmitted over the optical channel as shown in Fig. 1. Modulation using QAM, PAM, or phase shift keying (PSK) maps the bits to data symbols and arrange them in the data vector $x\,(k)$. It is assumed that the number of available subcarriers is N, the number of guard subcarriers is N_g, B is the channel bandwidth and $m = \log_2(M)$ where M is the size of the considered constellation diagram.

In ACO-OFDM, only odd subcarriers are modulated as follows,

$$s\,(k) = \begin{bmatrix} 0 & x\,(k) & 0 & x^*\,(N-k) \end{bmatrix}, k = 1, 3, \ldots, {}^{N}\!/_{2} - 1 \tag{1}$$

where $x^*\,(N-k)$ is the complex conjugate transpose of the input data vector $x\,(k)$ to produce a real signal at the output of the OFDM modulator [7, 9] and $x\,(k)$ contains data only at the odd numbered k. In addition, $s(0)$ and $s(N/2)$ are set to zero to ensure that the output consists of only real values. Therefore, the achieved data rate for ACO-OFDM system is given by,

$$R^{\{\mathrm{ACO}\}} = \left(\frac{{}^{N}\!/_{4} - 1}{N + N_g}\right) B\,\log_2 M \qquad \text{bits}/s. \tag{2}$$

The OFDM modulator converts $s(k)$ to the half-wave symmetry time signal $s(n)$. An example of $s(n)$ assuming $N = 16$ is depicted in Fig. 2. The half-wave symmetry of $s(n)$ means that the same information in the first $N/2$ samples is repeated in the second half of the OFDM symbol. As a consequence the negative part can be clipped without any loss of information. This clipping produces a unipolar signal. The unipolar signal is then used to intensity modulate the LED. At the receiver, the PD detects the transmitted intensity and AWGN is added [7].

An alternative system that produces half-wave symmetry output signal is the recently proposed PAM-DMT system [8]. PAM-DMT is proposed to increase the number of used subcarriers in ACO-OFDM system from $N/4 - 1$ to $N/2 - 1$. Thereby, the achieved data rate for PAM-DMT system is given by,

$$R^{\{\mathrm{PAM-DMT}\}} = \left(\frac{{}^{N}\!/_{2} - 1}{N + N_g}\right) B\,\log_2 M \qquad \text{bits}/s. \tag{3}$$

In PAM-DMT, the data symbols in $x\,(k)$ must be real, *i.e.* PAM symbols. The time signal $s\,(n)$ is then obtained by applying discrete sine transform on the real symbols,

$$s\,(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N/2-1} s\,(k) \sin\left(2\pi k \frac{n}{N}\right), \quad n = 0, 1, \ldots, N-1 \tag{4}$$

where $s(k)$ is a vector equivalent to $x(k)$ but with an additional first element set to zero, *i.e.* $s(0) = 0$. An example of the resultant $s\,(n)$ signal for $N = 16$ and $m = 2$ is shown in Fig. 2. The time signal is clipped at the zero level and the unipolar signal is used to modulate the LED intensity.

Half-wave symmetry OFDM systems have several advantages among of which are the following:

1) A DC biased is avoided which essentially means improved power efficiency.
2) A larger amplitude of the signal can be considered which covers the full dynamic range of the LED. This is indeed significant, as will be shown later, when considering the LED clipping effects.
3) It has been shown in [9] that the negative clipping noise in ACO-OFDM system falls on the even subcarriers only. Hence, it is orthogonal to the transmitted data on the odd subcarriers and has no significant impact on the performance.

Conversely, these systems suffer from several drawbacks as follows,

1) Half-wave symmetry OFDM transmission techniques sacrifice a significant portion of the available signaling bandwidth (typically up to 30 MHz).
2) For VLC (visible light communication) systems, a DC bias is needed for the lighting purposes which makes the clipping at the zero level redundant. These techniques seem more appropriate for IR wireless communication, but also in this case some minimum DC biasing is required corresponding to the LED turn-on voltage.
3) For PAM-DMT systems, the signal constellation is limited to real values only which suffers from larger probability of error as compared to QAM and PSK constellations.

B. DC-biased OFDM techniques

The second group contains two transmission schemes that produce no symmetrical signals and, therefore, require a DC-

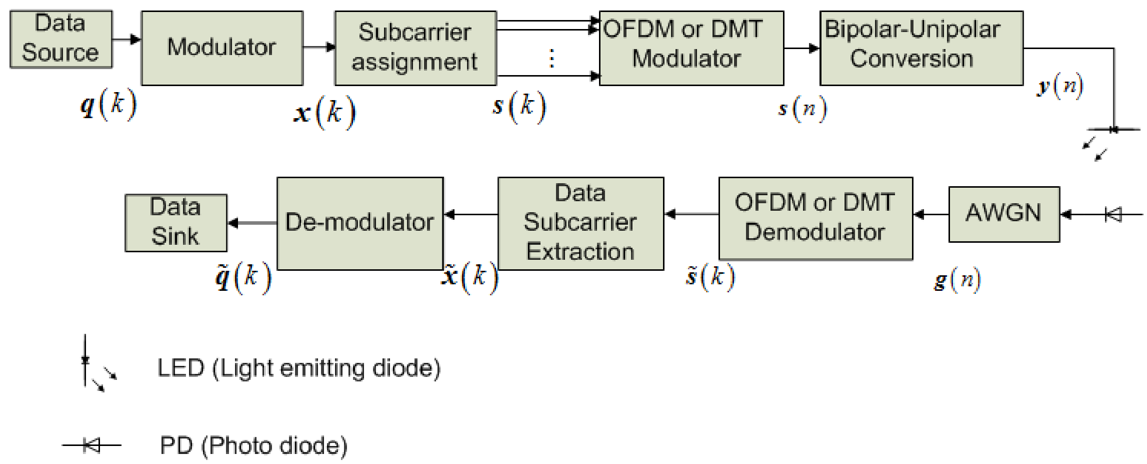

Fig. 1. Indoor OW OFDM system model

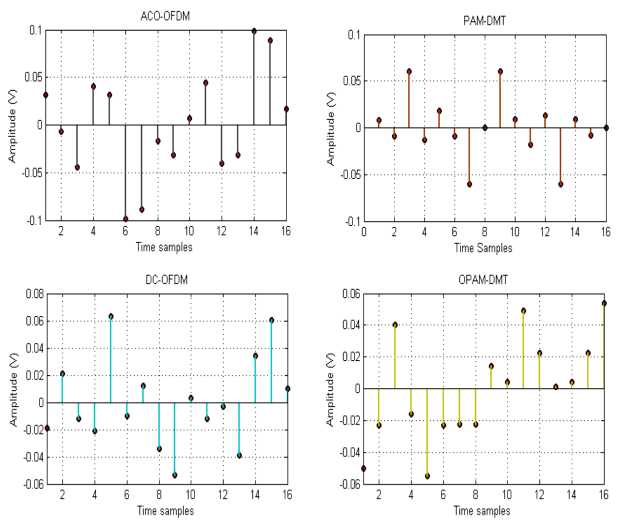

Fig. 2. The output OFDM time signals for ACO-OFDM, PAM-DMT, DC-OFDM, and OPAM-DMT systems for $N = 16$. Half-wave symmetry signals are achieved for ACO-OFDM and PAM-DMT systems. For DC-OFDM and OPAM-DMT, however, a DC biased must be used.

bias to produce a unipolar signal.

The first scheme called DC-OFDM [5–7] assigns data to subcarriers as follows,

$$s(k) = \left[\begin{array}{cccc} 0 & x(k) & 0 & x^*(N-k) \end{array}\right], \quad k = 1, 2, \ldots, {}^{N}\!/_{2}{-}1 \tag{5}$$

where data is assigned to all odd and even subcarriers and $x(k)$ is a vector containing data symbols from a complex signal constellation diagram. The OFDM modulator is applied to $s(k)$ producing a time signal as shown in Fig. 2. The time signal is bipolar and DC bias is needed to shift the negative values to positive values before modulating the LED intensity. The DC bias value depends on the LED characteristics and can significantly affect system performance [10, 11]. The data rate of DC-OFDM system can be calculated using the same equation given in (3).

Another new scheme that belongs to this group and is proposed in this paper for the first time is called OPAM-DMT. In OPAM-DMT, discrete sine and cosine transforms are used to transmit data simultaneously. This results in a doubling of the data rate as compared to PAM-DMT. The time signal is the summation of two orthogonal signals $s(n) = s_1(n) + s_2(n)$. $s_1(n)$ is obtained as in (4) and $s_2(n)$ is calculated as follows,

$$s_2(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N/2-1} s_1(k) \cos\left(2\pi k \frac{n}{N}\right), \; n = 0, 1, \ldots, N-1 \tag{6}$$

were $s(k)$ and $s_1(k)$ are two independent data streams. A sample of the resultant time signal is depicted in Fig. 2. Again, the signal is bipolar and DC-bias must be used. The data rate of OPAM-DMT is given by,

$$R^{\{\mathrm{OPAM-DMT}\}} = 2\left(\frac{{}^{N}\!/_{2} - 1}{N + N_g}\right) B \log_2 M \qquad \mathrm{bits/s}. \tag{7}$$

In summary, DC-biased OFDM systems achieve higher data rates as compared to half-wave symmetry OFDM systems, but they are subject to several issues:

1) The DC bias results in an additional power consumption which reduces the power efficiency of these systems.
2) The LED nonlinearity and clipping effects are more significant and highly depends on the considered bias point. Also, the bias point reduces the LED dynamic range as compared to half-wave symmetry OFDM transmission approaches. This limits the transmitted optical power.

III. Simulation Results

In the analysis, a high power IR LED (OSRAM, SFH 4230) is considered [12]. The LED nonlinearity behavior can be well compensated by using a predistorter [13]. Therefore, in this paper, only clipping effects are considered. For the considered LED with predistorter, a lower clipping value at 1.5V, which is slightly higher than the turn-on-voltage of the LED, and a higher clipping value at 2V are considered. The higher clipping is needed to ensure that the LED does not overheat, in order to avoid degradation in output light or, in the worst case, total failure. For DC-biased transmission, a DC bias of 1.75V is considered which corresponds to the center of the considered LED operating range.

The performance of half-wave symmetry OFDM transmission is depicted in Fig. 3 for ACO-OFDM and in Fig. 4 for PAM-DMT. Similarly, the performance of DC-biased OFDM systems is depicted in Fig. 5 for DC-OFDM and in Fig. 6 for OPAM-DMT. In all figures, uncoded transmission is considered. The x-axis represents the average electrical OFDM signal power before modulating the LED and the y-axis denotes the achieved BER for different modulation orders. The OFDM signal power is varied from 0 dBm to 30 dBm and an AWGN power of -10 dBm is assumed. As a result, the simulated electrical signal-to-noise-ratio (SNR) range is from 10 dB to 40 dB which is within the reported SNR values for indoor OW systems [14]. The achieved data rate for each system and for each modulation order is calculated and reported in the caption of each figure. In addition, a channel bandwidth of $B = 20$ MHz, a number of subcarriers of $N = 64$, and a number of guard interval subcarriers of $N_g = 2$ are considered [2, 7]. In half-wave symmetry systems, signal amplitudes larger than 0.5V are clipped. For DC-biased OFDM systems, signal amplitudes larger than 0.25V and lower than -0.25V are clipped.

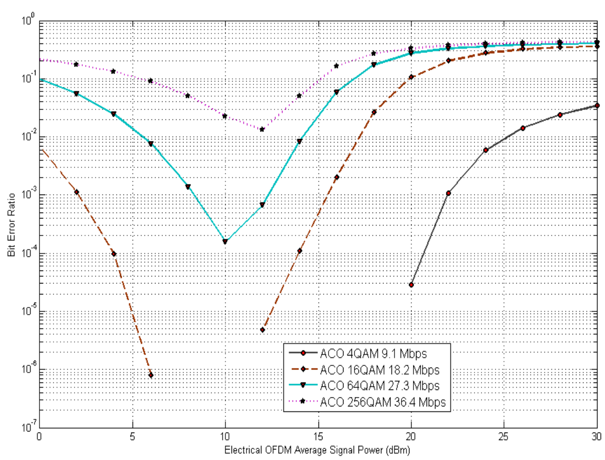

Fig. 3. ACO-OFDM system performance for different QAM modulation orders.

By observing the performance of all systems, the following trends can be observed:

- The performance highly depends on the considered modulation order. The time domain OFDM signal envelope suffers from high peak values. High peak signal values in OFDM stem from the superposition of a large number of usually statistically independent sub-channels that can constructively sum up to high signal peaks in the time domain. The higher the modulation order and/or the number of subcarriers, the higher the expected peak values.

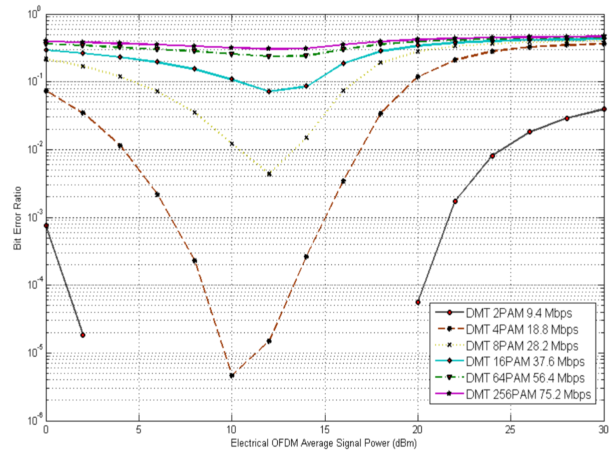

Fig. 4. PAM-DMT system performance for different PAM modulation orders.

- At low OFDM signal powers, the performance is noise dominant while the clipping effects dominate at high signal power. In all considered systems, it can be found that there is an optimum power. The discontinuity in some of the BER curves indicate that the simulated BER was zero for the corresponding OFDM signal powers. The optimum value depends on the considered LED characteristics and modulation order. Therefore, system design must consider the LED characteristics and optimize the transmitted signal power to avoid significant performance degradation.
- Performance enhancement for all systems, when increasing the power from 0 dBm to the optimum value can be explained by the increase in the SNR and the absence of signal clipping at low amplitudes.
- Similarly, performance degradation when increasing the signal power beyond the optimum value is due to clipping distortion.
- At low data rates, DC-biased OFDM systems perform better than half-wave symmetry OFDM systems. This can be attributed to the required larger modulation orders by half-wave symmetry systems to compensate for the incurred rate loss. For example, 4-QAM DCO-OFDM system demonstrates zero BER at 15 dBm OFDM signal power while the BER for 16-QAM ACO-OFDM system at the same signal power is around 5×10^{-3}. A similar behavior can be noticed when comparing 2-PAM OPAM-DMT and 4-PAM PAM-DMT systems.
- High Modulation orders, such as 64-QAM and 256-QAM, are very sensitive to clipping distortions and increasing signal powers beyond the optimum value becomes futile.
- Finally, results show that data rates higher than 40 Mbps cannot be achieved at BER values of about 10^{-4}. However, it is anticipated that different LEDs with larger dynamic range will result in better BER performance.

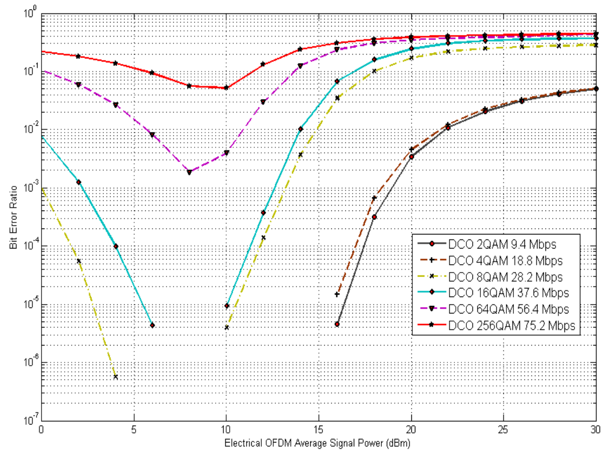

Fig. 5. DC-OFDM system performance for different QAM modulation orders.

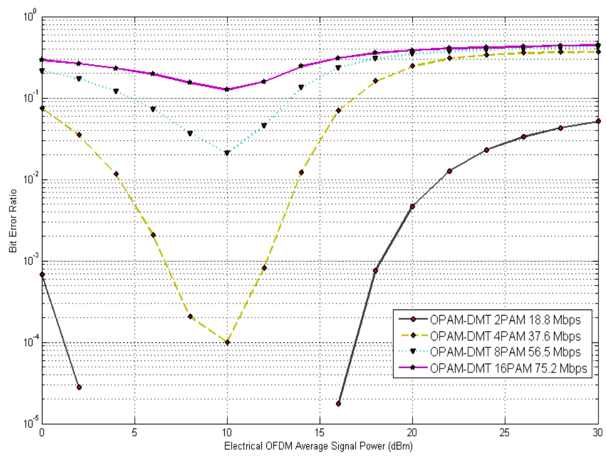

Fig. 6. OPAM-DMT system performance for different PAM modulation orders.

IV. Conclusions

This paper proposes a novel OW OFDM transmission scheme and provides an overview of existing indoor OW OFDM transmission techniques. The novel OPAM-DMT scheme is an extension to the recently proposed PAM-DMT technique by considering discrete sine and cosine transforms. Existing indoor OW OFDM techniques are categorized based on the way data is assigned to subcarriers and the bipolar-unipolar conversion process. The first group of OW OFDM techniques produces half-wave symmetry time signals and allow clipping at the zero level. Thus, reducing DC power consumption by avoiding the need for a DC bias. These advantages are achieved at the expense of a major reduction in data rate as compared to DC-biased OFDM systems. The performance of these systems in the presence of LED clipping clearly highlights the significant dependence on the considered modulation order. It is shown that high modulation orders are impractical for large signal power. It is also shown that AWGN noise dominates at low SNR values and clipping distortion dominates at large SNR values. Therefore, system design should consider LED clipping effects and should optimize the OFDM signal power and the considered modulation order.

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